PULSARS AND X-RAY EMITTING
SUPERNOVA REMNANTS

STEPHEN S. HOLT
REUVEN RAMATY

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GSFC ——— **GODDARD SPACE FLIGHT CENTER** ———
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NASA, Goddard Space Flight Center

Greenbelt, Maryland, U.S.A.

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We address ourselves to the possible existence of pulsars in known supernova remnants. Specifically, those remnants with observable X-ray luminosity are particularly attractive candidates since, if such emission is non-thermal in origin, a contemporary source of high-energy electrons is required to maintain the X-ray output. By analogy with the Crab Nebula, the energy required for the continual acceleration of those electrons may reside in a rotating neutron star.

X-ray spectra from Cas A and SN 1572 (Tycho's supernova) were recently reported.[1] The relevant data for these remnants and for the Crab Nebula are summarized in Table 1.

Table 1 - Relevant Parameters

	Crab	Cas A	Tycho
Age[2] (yr)	915	267	397
Distance[2] (kpc)	1.8	3.4	5.0
X-Ray Spectrum[1] (keV/cm^2-sec-keV)	$9E^{-1.0}$	$3.7E^{-2.3}$	$.44E^{-1.3}$
Absolute Luminosity Relative to the Crab,f	1(1 keV-1 MeV)	.16($>$1 keV)	.19($>$1 keV)

In computing the X-ray luminosities from the measured spectra and the distances, we remark that such luminosities include only photons with energies greater than 1 keV. The measured spectra of Cas A and Tycho do not extend below this energy, but since both these spectra are

steeper than that of the Crab Nebula, the relative luminosities quoted are probably lower limits.

We assume that there exists a rotating neutron star in the nebula of each of these remnants. The rate at which rotational energy is lost by these objects is:

$$- \frac{dT}{dt} = c_1 B_0{}^2 P^{-4} + c_2 P^{-6} + c_3 P^{-1} \tag{1}$$

where P is the rotation period, and the three terms represent electromagnetic, gravitational and mass loss components of the total energy depletion rate, respectively. We begin by assuming that the first term dominates, whether it be the oblique rotator[3] or axysymmetric[4] case, i.e. whether B_0 is the perpendicular or parallel component of the surface magnetic field of the neutron star.

In general, since the acceleration of high-energy particles should be the consequence of the stellar electromagnetic energy loss, we expect that the X-ray luminosity of the nebula will be proportional to this mode of energy depletion. If we assume that the acceleration efficiency in a given nebula is the same as in the Crab, and if the moment of inertia and radius of the embedded neutron star are the same as those of the Crab nebula pulsar, we can use the known ages and measured X-ray luminosities of the candidate nebula and of the Crab, as well as the period of the Crab pulsar, to determine both the period and surface field of the postulated neutron star. These are given by

$$P = P_{Crab} \left[\frac{1}{f} \frac{t'_{Crab}}{t} \right]^{1/2} \tag{2}$$

$$B_0 = B_0^{Crab} \frac{1}{f^{1/2}} \left[\frac{t'_{Crab}}{t} \right] \tag{3}$$

Numerical values for Cas A and Tycho are given in Table 2.

Table 2 - Deduced Values of P and B_0 for

Electromagnetic Energy Loss

	Crab	Cas A	Tycho
P(msec)	33	<173	<130
$B_0(10^{12}$ gauss)	2.6	<28.5	<17.6

We have used the ages (t) of Cas A and Tycho given in Table 1, while

the Crab age (t'_{Crab}) used was 1170 years, the "electromagnetic" age

deduced by Ostriker and Gunn.[5] This is consistent with our initial

assumption that the Cas A and Tycho losses are strictly electromagnetic,

while the Crab losses are not. These authors have also obtained B_0^{Crab} =

2.6×10^{12} gauss for "typical" neutron star parameters and the period

and rate of change of the period of the Crab Nebula pulsar.

The values listed in Table 2 are upper limits because the relative

luminosities f of Cas A and Tycho are lower limits, and both P and B_0

are proportional to $f^{-1/2}$. Furthermore, if we allow the addition of

gravitational quadrupole radiation to the rotational energy loss, the

periods and fields of Table 2 are further reduced, so that they are

upper limits in this sense as well. The addition of gravitational

radiation may be investigated in terms of the parameter

$$R = \left[\frac{c_1}{c_2} B_0^2 P^2 \right]^{-1} \tag{4}$$

which is the present ratio of gravitational energy loss to electromagnetic energy loss.(R is equal to the quantity η_t^{-1} used by Ostriker and Gunn[5] ; from the discrepancy between the "electromagnetic" age, mentioned above, and the real age of the Crab Nebula, they find $R \approx .2$ for the Crab Nebula pulsar). Equations (2) and (3) then become

$$P = P_{Crab} \left[\frac{1}{f} \frac{t'_{Crab}}{t} \right]^{1/2} \left[1 - R \ln (1 + \frac{1}{R}) \right]^{1/2} \quad (5)$$

$$B_0 = B_0^{Crab} \left[\frac{1+R}{f} \right]^{1/2} \frac{t'_{Crab}}{t} \left[1 - R \ln (1 + \frac{1}{R}) \right] \quad (6)$$

The periods and surface fields derived from Equations (5) and (6) are given in Table 3.

Table 3 - Upper Limits for P and B_0

For Various Values of R

	Cas A		Tycho	
R	P	B_0	P	B_0
0	173	28.5	130	17.6
.3	129	18.2	97	11.2
.5	116	15.7	87	9.7
1.0	96	12.4	72	7.6
2	75	9.3	57	5.8
5	51	6.2	39	3.8
10	37	4.5	28	2.7
50	17	2.0	13	1.2
100	12	1.4	9	0.9

It would appear that the values of P and B_0 for the postulated pulsars in Cas A and Tycho can be arbitrarily decreased merely by invoking large amounts of gravitational radiation. According to the analysis of Ostriker and Gunn,[5] however, the stellar deformation which gives rise to the gravitational radiation is field-dependent. The constant C_2, which is proportional to the square of the component of the mass-quadrupole moment perpendicular to the rotation axis, is also proportional to the fourth power of the interior neutron star field. Assuming that the relationship between the interior and surface fields is the same for the three objects considered, and since the parameter C_1 was also assumed to be the same, we obtain that

$$R \propto \frac{B_0^2}{P^2} \tag{7}$$

Using Equations (5) and (6) and R = 0.2 for the Crab Nebula pulsar, we find that R = 0.6 for Cas A and R = 0.4 for Tycho. The corresponding periods for both objects then become about 100 ms, less than a factor of two below the absolute upper limits given in Table 1. The invocation of gravitational radiation, therefore, does not significantly modify the deduced upper limits.

Regarding the important question of the observability of such pulsar candidates, it is obvious that a whole new set of assumptions must be made since the previous arguments were not dependent upon any specific radiation mechanism. One possibility is to assume direct scaling with the Crab Nebula, i.e. to assume that the pulsed fraction in the X-ray band is the same as that in the Crab, and the pulsar

electromagnetic spectrum is the same. This would imply that the pulsed

fraction in X-rays would be about 10%[6,7,8,9], but the radio pulse would

be below the sensitivity of the NRAO pulsar survey[10] (in which Cas A and

Tycho were not found). The same experiment which we have quoted for

the X-ray luminosities[1] also places limits on the X-ray pulsation of

these sources. For a pulse width of 0.1 of P, for the range 8 msec $<$

P$<$35 msec, upper limits to the pulsed fraction of 15% and 19% for Cas A

and Tycho were quoted. Aside from the obvious remark that the expected

periods are probably higher than 35 msec, the sensitivity even in this

period range to an arbitrary pulse shape is considerably worse, as

evidenced by the fact that a 10% upper limit (i.e. not a positive result)

was obtained for the pulsed fraction from the Crab Nebula.

Perhaps a more reasonable, but not as objective, an approach would

be to consider a specific emission model, such as that proposed by

Bertotti, Cavaliere and Pacini.[11] In this model, the pulsar emission

is peaked in two bands surrounding the characteristic frequencies:

$$\nu_1 \approx \frac{\gamma_1^2}{P} \qquad \text{(radio peak)}$$

$$\nu_2 \approx \frac{eB_L \gamma_2^2}{2\pi mc} \qquad \begin{array}{l}\text{(optical and} \\ \text{X-ray peak)}\end{array}$$

where B_L is the magnetic field at the speed of light circle. For the

Crab Nebula pulsar, γ_1 and γ_2 are both taken to be $\sim$ 200. Using the

same values for the candidate pulsars in Cas A and Tycho, the X-ray

pulsed fraction in these objects is considerably suppressed, since

the magnetic field at the speed of light circle is smaller—this

results in both a movement of the peak to lower frequencies and a decrease in the total power in the pulse. For the case of $P \approx 100$ msec ($\sim 3\ P_{Crab}$) and $B_0 \approx 10^{13}$ gauss ($\sim 4\ B_0^{Crab}$) (the upper limits deduced previously), the speed of light circle is three times farther out than in the Crab so that the near dipole field at the speed of light circle is almost an order of magnitude below its value in the Crab. Since the pulsed fraction (in terms of total energy) varies like P^{-2} (because the nebular luminosity varies like $B_0^2\ P^{-4}$ and the pulsar emission as $B_0^2\ r_L^{-6}$, where $r_L = CP/2\pi$ is the radius of the speed-of-light circle), the combination of decreased power and centering of the pulse at lower frequencies demanded by this model reduces the X-ray pulsed fraction to less than 1%.

Such small pulsed fractions could not be detected from these relatively weak X-ray sources with the exposures available in rocket experiments at the present time. If, however, the fraction f is larger than the lower limit we have used, the deduced pulsed fraction will increase since it varies as P^{-2}, and the field dependence cancels out in the dipole model we have used. For example, if we assume that both the Crab and Cas A spectra can be extended down to 100 eV rather than the 1 keV cutoff used in the above analysis, f for Cas A increases by a factor of 15 and the pulsed fraction increases by a like amount. It would not be unreasonable, therefore, to expect Cas A and Tycho to exhibit observable ($\lesssim 10\%$) X-ray pulsation with periods which do not greatly exceed that of the Crab. Since we do not know how the nebular spectra cut off in the ultraviolet, however, such speculation can only be qualitative.

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